AIRBORNE MEASUREMENTS OF WHITECAP KINEMATICS AND DYNAMICS IN THE HIGH-WIND REGIME: SOURCE FUNCTIONS FOR MARINE AEROSOLS, SURFACE CURRENTS AND TURBULENCE

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LONG-TERM GOALS

The long-term goals of this research are to improve our knowledge and understanding of the role of breaking in air-sea interaction. We are concerned with the role of breaking in the fluxes of momentum, energy (mechanical and heat) and mass (gasses & aerosols) across the air-sea interface. These processes are important for the generation of ocean currents, air-sea heat and gas transfer , surface-wave evolution and dissipation, upper ocean mixing and transport, and hurricane dynamics (Melville, 1996).

OBJECTIVES

The objectives of this effort are to demonstrate that visible and infrared remote sensing of whitecaps can be used to improve models of momentum transfer, turbulent mixing and aerosol generation in the high-wind and hurricane regime.

APPROACH

Our approach, which was first developed in the ONR Shoaling Waves Experiment (SHOWEX), is to use modern quantitative imaging techniques to measure the kinematics of breaking in the field and relate it to the fluxes of momentum, energy and mass across the air-sea interface through the use of simple scaling arguments and models.

The basis of the approach is the statistical description of breaking at the ocean surface in terms of $\Lambda(\mathbf{c})d\mathbf{c}$, the average length of breaking fronts per unit area of ocean surface moving with velocities in the range ($\mathbf{c}$, $\mathbf{c}+d\mathbf{c}$). This was introduced by Phillips (1985) who showed how the kinematics and dynamics could be related through simple scaling

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arguments (Duncan, 1981) that showed that the loss of energy from the wave field per unit length of breaking front was proportional to $\rho g^{-1} c^5$. This permitted Phillips to predict the breaking statistics for an equilibrium wave field in which there was a balance between wind input, wave-wave interactions and dissipation due to breaking.

Airborne visible imagery and motion instrumentation permit the measurement of $\Lambda(\mathbf{c})d\mathbf{c}$ in the field. This was attempted in SHOWEX, using the methods of particle imaging velocimetry (PIV) to measure the kinematics of breaking in an Earth frame and thereby measure $\Lambda(\mathbf{c})d\mathbf{c}$**.** In Melville & Matusov (2002) the results of those measurements from the LongEZ aircraft are presented along with supporting measurements of the wave field.

In the CBLAST hurricane program our approach is to fly the imaging equipment (both visible and IR) along with a laser altimeter on the NOAA "Hurricane Hunter" P3s based at MacDill airbase in Tampa, Florida. The laser altimeter has a useful range of 200-250m and will give direct wave information bore-sighted with the images at low aircraft altitudes. This will permit coherent processing of the image and wave data to determine the characteristics of the breaking waves. At higher altitudes we expect to collaborate with Ed Walsh of NOAA who is making radar wave measurements.

Measurements of $\Lambda(\mathbf{c})d\mathbf{c}$ and its moments will be used to infer surface renewal by breaking, whitecap coverage, mixing by breaking and the momentum and energy fluxes from waves to the mixed layer. Since the bubbles and sea spray generated by breaking are proportional to $\Lambda(\mathbf{c})d\mathbf{c}$ (and perhaps other variables) we will work to interpret our measurements in the context of improved models of sea-spray generation. We will also develop image-processing algorithms to distinguish between whitecapping and the spume/spray generated by high winds shearing off the crests of the waves. Sea spray is an important contributor to the heat transfer in high winds and improved measurements and models of spray generation will lead to improved hurricane models.

Apart from the co-PIs, the key individuals working on this project have included Peter Matusov and Jim Lasswell who have developed the imaging hardware and acquisition software, and Jessica Kleiss, a graduate student, who has analyzed the data.

WORK COMPLETED

Funding for this project began in December 2001. During the 2002 hurricane season, several "engineering" flights were flown in hurricane Isidore to test the visible imaging system and the laser altimeter for surface wave measurements. Analysis of that data led to preliminary estimates of whitecap coverage and breaking statistics in Isidore. These results were reported at the CBAST Hurricane Workshop in Miami early in 2003.

With the experience from the 2002 hurricane season, a significant redesign of the image acquisition hardware and software was undertaken. The IR imaging system was prepared for installation in the P3 (N43RF) for the 2003 hurricane season.

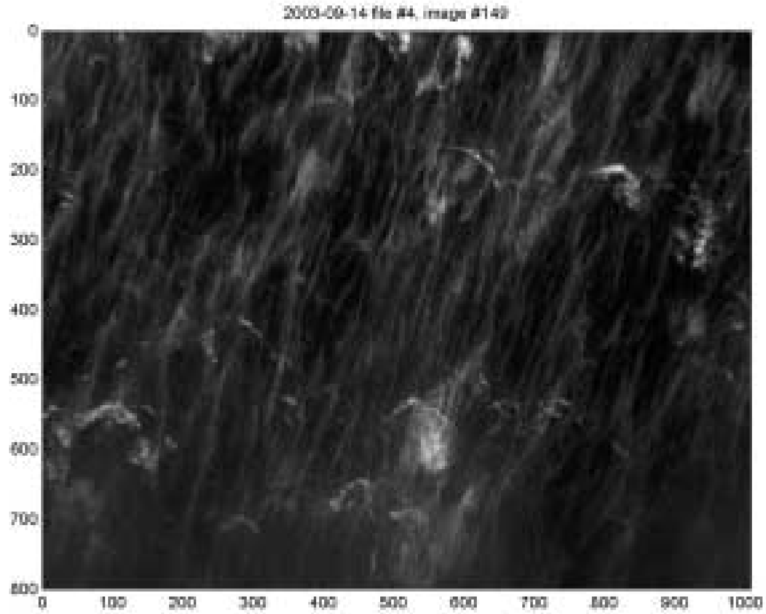

Fig. 1: Image captured 9/14/2003, altitude 1210 m, at 66.85W, 24.78N, just to the north of the eye of hurricane Isabel. Note the crescent-shaped breakers (O(100) m along the crest), all oriented towards the top of the image, and streaks oriented perpendicular to the breaking direction. This mix of breaking and foam/spray streaks are common features of the visible imagery.

The visible imaging system and the laser altimeter (for wave measurements) were installed on N43RF for the hurricane season. However, due to other commitments, the engineering/technical staff at MacDill are still working on installation of the IR imaging system on N43RF. We hope it will be installed for at least one test flight this year.

The visible imaging system and laser altimeter were flown in hurricanes Fabian and Isabel. Camera problems led to the acquisition of substandard images during Fabian. A change in lenses led to significant improvements in the imagery during Isabel (see Figure 1.) The combination of whitecaps and streaks of foam/spray (the latter being roughly aligned with the wind) are a common feature of the imagery. Distinguishing between foam and airborne spray remains one of the primary tasks in the analysis of these data.

Figure 2 shows a montage of a satellite image of hurricane Isabel, the hurricane track and preliminary estimates of whitecap coverage. The variability of the breaking activity as measured by the whitecap coverage is one of the striking aspects of these preliminary data. In addition to the variations in whitecap coverage seen at the scales of the hurricane, the data (not shown here) show significant variability at O(km) scales. This is presumably due to the modulation of the wind and waves at these scales, and the causes should become more apparent as we proceed with data analysis.

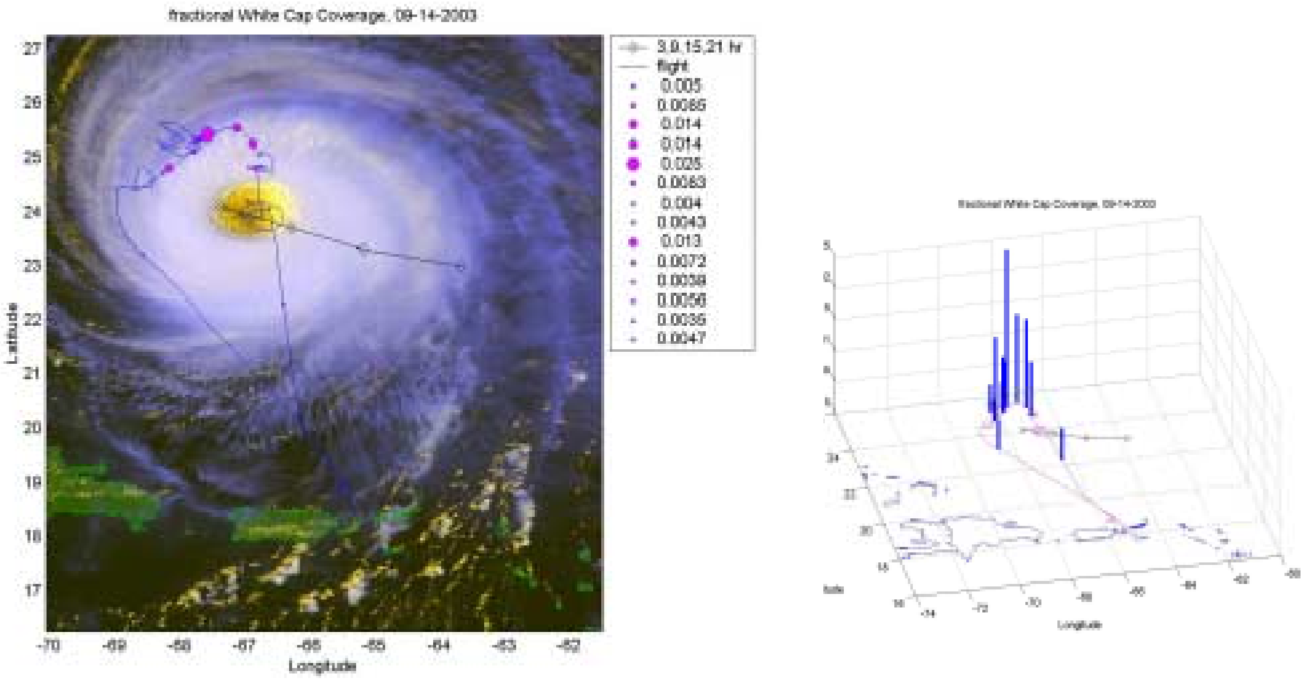

Fig. 2a: Preliminary analysis of visible imagery. Satellite image of hurricane Isabel from the NOAA-16 satellite AVHRR 3 channel color composite image captured at 18:42Z, 9/14/2003 (from Ray Sterner). The diamonds indicate the hurricane eye at 0300, 0900, 1500, and 2100 hours as it moved west. N43RF ground track is plotted in blue. The pink dots indicate the fractional white cap coverage (area of white caps/total area in image) for 14 flight segments where sea surface images were recorded. Segments last approximately one minute, or 8km. Actual numerical values for white cap coverage are listed in the legend. Fig. 2b: Perspective plot of whitecap data in Fig. 2a.

Understanding the variability of the whitecap statistics will depend in part on the laser altimeter data. The altimeter has a pulse repetition frequency of 12 kHz which is binned down to 120 Hz, giving a spatial sampling of the ocean surface at O(1) m intervals. It was expected that the altimeter would function satisfactorily at altitudes of up to 300m; however, our experience in hurricane Isabel was that the maximum useful altitude was approximately 200-250 m, still very satisfactory since the aircraft was able to do stepped descents down to approximately 60 m.

Figure 3 shows examples of preliminary (raw) altimeter data uncorrected for aircraft attitude and speed fluctuations. The time series have been converted to spatial series by using the average speed of the aircraft over the duration of the data segment, and wave number spectra calculated. The time series clearly show excursions well beyond the amplitude of the surface waves and at longer scales. These we attribute to aircraft motion and attitude changes. The one-dimensional spectra all have slopes of approximately k^{-3}, in the range 0.1-1 rad/m, consistent with the data of Melville & Matusov (2002) in this range of wavenumbers.

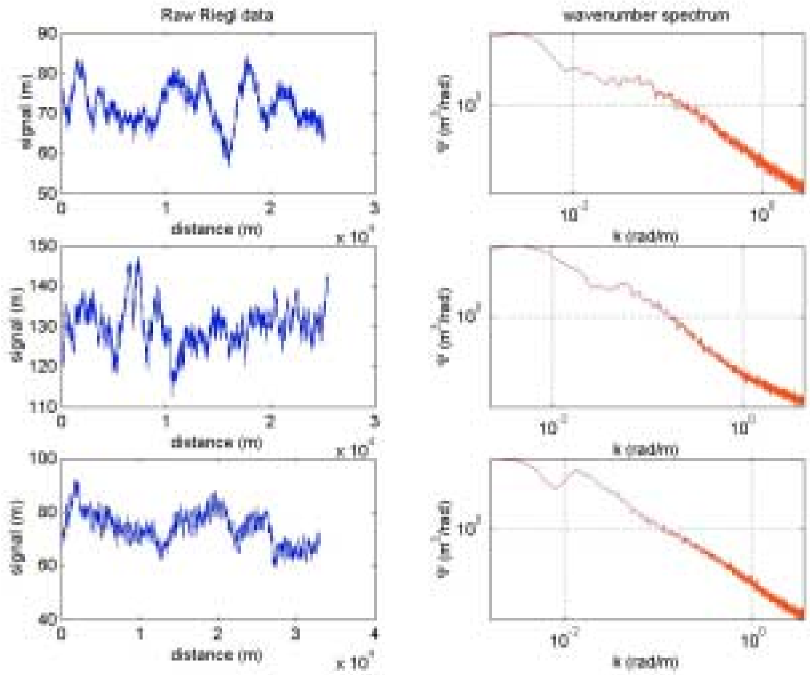

Fig.3: Preliminary selection of laser altimeter spatial series (derived from time series and aircraft speed) and wavenumber spectra from hurricane Isabel on 9/14/03. We believe that the large-scale fluctuations in the record are due primarily to aircraft motion and attitude changes.

While this is a very preliminary look at the visible imagery and laser data from hurricane Isabel, we expect that more detailed analysis will prove very useful in correlating the incidence of breaking with the wind and wave parameters.

RESULTS

During the first two years we have overcome most of the technical issues of using our equipment on the NOAA P3s and participating in hurricane flights. The IR imager is still to be incorporated into the suite of instruments. Methods of data/image analysis are being developed to more fully exploit the data. With the hurricane season still active our efforts have been concentrated on acquiring data and testing equipment rather than producing finished technical results. Results shown here are preliminary.

IMPACT/APPLICATIONS

We expect this project will produce valuable data and models to represent the role of surface-wave breaking and whitecapping for air-sea interaction in hurricane winds.

TRANSITIONS

None yet.

RELATED PROJECTS

This project is closely related to other P3-based projects in CBLAST/Hurricane under the leadership of Peter Black as Chief Scientist. We expect to collaborate most closely with Peter Black and Ed Walsh in relating our measurements of breaking to the atmospheric and wave variables they will measure.

The PIs have another CBLAST project ("Autonomous profiler measurements of the air-sea interface in very high sea states", N00014-00-1-0894; Terrill, PI) that has developed an air-deployed variant of the PALACE float to provide high frequency, high resolution upper mixed layer and wave measurements under hurricanes. The projects will permit us to correlate the mixed layer profiles with mixing and air entrainment due to breaking. During the 2003 hurricane season two floats were air-deployed and one recovered.

Ken Melville is collaborating with Peter Sullivan and Jim McWilliams to incorporate breaking into DNS and LES models of coupled boundary layers. Sullivan and McWilliams are supported under CBLAST (N00014-00-C-0180; Sullivan, PI)

The PIs (along with Dariusz Stramski) are participants in ONR's HYCODE program. Our component of this program is using acoustical and optical techniques to measure entrained air in the marine wave boundary layer (MWBL) and its effects on the inherent optical properties of near surface waters (N00014-02-1-0190; Terrill, PI).

The PIs are collaborating in the ONR Rough Evaporation Duct Experiment (RED), measuring bubbles and breaking waves in support of estimates of the source functions for marine aerosols which are important in em propagation. (N00014-01-1-0701; Terrill, PI).

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